Global Persistent SAR Sampling with the NASA-ISRO SAR (NISAR) Mission

Paul A. Rosen, Yunjin Kim
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA, 91109

Raj Kumar, Tapan Misra, Rakesh Bhan
ISRO Space Applications Centre, Ahmedabad, India

V. Raju Sagi
ISRO Satellite Centre, Bangalore, India

Abstract—**The National Aeronautics and Space Administration (NASA) in the United States and the Indian Space Research Organisation (ISRO) are developing an Earth-orbiting science and applications mission that will exploit synthetic aperture radar to map Earth's surface every 12 days, persistently on ascending and descending portions of the orbit, over all land and ice-covered surfaces. The mission's primary objectives will be to study Earth land and ice deformation, and ecosystems, in areas of common interest to the US and Indian science communities. This single spacecraft solution with an L-band (24 cm wavelength) and S-band (10 cm wavelength) radar has a swath of over 240 km at fine resolution, using full polarimetry where needed, uses a reflector-feed system whereby the feed aperture elements are individually sampled to allow a scan-on-receive ("SweepSAR") capability at both L-band and S-band. This design is in contrast to recent concepts towards large constellations of smaller radar satellites, and is driven by the science requirements for complete coverage over the 12-day repeat cycle, using repeat pass interferometry and polarimetry to measure deformation and surface properties. A single spacecraft with enough aperture, power, duty cycle, and downlink capacity was determined to be a more practical and implementable solution that multiple smaller spacecraft. The use of a single large aperture reflector for both the L- and S-band radars enables both to have comparable performance, leading to overall development and operational efficiencies.**

I. Introduction

Since the 2007 National Academy of Science "Decadal Survey" report "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" [1], NASA has been studying concepts for a Synthetic Aperture Radar (SAR) mission to determine Earth change in three disciplines – ecosystems, solid earth, and cryospheric sciences. NASA is now partnered with the Indian Space Research Organisation (ISRO) to develop the mission [2]. The NASA-ISRO SAR (NISAR) mission will expand on previous NASA concepts that exploited an L-band array-fed reflector SAR configuration to enable > 200 km swath at full SAR resolution and full polarimetry simultaneously [3,4], necessary to meet the requirements in all three disciplines. As the partnership concept with ISRO developed, it became clear that flying dual L- and S-band SAR capabilities, with L-band electronics supplied by NASA and S-band electronics by ISRO, will satisfy science and application requirements of the US and India. A dual-frequency fully polarimetric SAR with the potential for global coverage every 12 days will offer unprecedented capability that researchers could exploit in new and exciting ways, and the compactness of the electronics on the feed structure will allow for addition of the S-band electronics, sharing the reflector aperture for directivity at both frequencies.

NASA and ISRO both have great interest in the global science objectives relating to the cryosphere, ecosystems, and the solid earth. These objectives will be primarily addressed with the L-band radar system, which is being designed for a

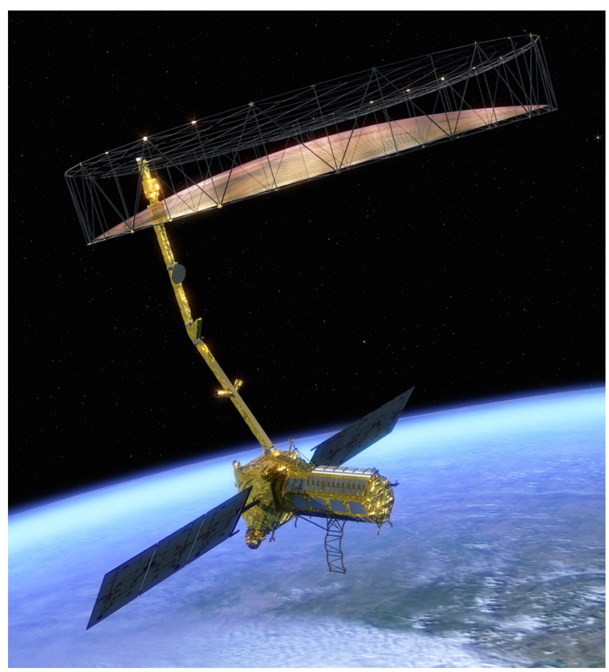

Figure 1. Artist's concept of NISAR spacecraft in flight configuration. Spacecraft velocity vector will be aligned with the long axis of the solar arrays. The L-band and S-band radar electronics are mounted on the octagonal structure pointing to the right.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

high on-orbit duty cycle. In addition, ISRO has a number of applications areas that drive their motivation for adding an S-band capability to the spacecraft, primary among these being agricultural biomass estimation, but also snow and glacier studies in the Himalayas, coastal winds and bathymetry, coastal processes, and hazard monitoring. Details of the science and applications of the mission concept are given in [2]. In addition, scientists involved in the mission definition are eager to explore the benefits of dual-frequency observations on selected global sites for a variety of applications. The S-band instrument is envisioned to have a shorter on-orbit duty cycle than the L-band instrument.

The NISAR partnership between NASA and ISRO will expand on previous collaborations on ISRO's Chandrayan-1 lunar and Mangalyaan Mars missions, and on NASA's QuikSCAT and ISRO's OCEANSAT Earth observation missions. NISAR will be the first where the technical and programmatic contributions are balanced at the mission level, with major hardware contributions from both organizations, described below.

The spacecraft will launch on an ISRO GSLV-II launch vehicle into a polar sun-synchronous dawn dusk orbit. The GSLV-II has experienced three consecutive successful launches since transitioning to entirely Indian-built technologies.

II. MISSION AND PARTNERSHIP CHARACTERISTICS

Many of the mission characteristics have been reported previously [5]. Sections II and III of this paper give some updated parameters and status. It should be noted that the mission requirements, and overall design have been quite stable during formulation and early development. Table 1 summarizes the overall mission characteristics. The spacecraft will accommodate two fully capable synthetic aperture radar instruments, each designed as array-fed reflectors to work as scan-on-receive wide swath mapping systems, hereafter referred to as "SweepSAR". The mapping scenario calls for frequent sampling over broad areas to create time series and allow for noise reduction through stacking methods. Thus, a high-rate instrument and data downlink system are required. The average capacity of the envisioned data downlink will be of order 26 Tbits per day, supporting the instruments which can produce at L-band from 91 Mbps in its lowest bandwidth mode to over 3100 Mbps in the most demanding high-bandwidth, multi-polarization mode. The S-band instrument has modes with similar data rates.

NASA contributions will include the L-band SAR instrument, including the 12-m diameter deployable mesh reflector and 9-m deployable boom and the entire octagonal instrument structure shown in Figure 1. In addition, NASA will provide a high capacity solid-state recorder (order 9 Tbits), GPS, 3.5 Gbps Ka-band telecom system, and an engineering payload to coordinate command and data handling with the ISRO spacecraft control systems. ISRO will provide the spacecraft and launch vehicle, as well as the S-band SAR electronics to be mounted on the instrument structure. ISRO will also contribute a 2.9 Gbps Ka-band telecom system, sharing their gimbaled downlink antenna with the NASA-telecom system. This ISRO telecom system is primarily intended to downlink S-band radar data. The coordination of technical interfaces among subsystems will be a major focus area in the partnership.

NASA and ISRO will share science and engineering data captured at their respective downlink stations, and each organization will maintain their own ground processing and product distribution system. It is anticipated that the science teams and algorithm development teams at NASA and ISRO will work jointly to create a common set of product types. The project will deliver NISAR data to NASA and ISRO for archive and distribution. NASA and ISRO have agreed to a free and open data policy for these data.

TABLE I. NISAR MISSION PROPOSED CHARACTERISTICS

Element	Description
Proposed Launch Date	Late 2021
Orbit	12-day exact repeat, sun-synchronous, dawn-dusk, polar, ~740 km altitude
Mission Duration	3 years nominal, with extended mission fuel reserve
Science Data Downlink Approach	• 30-50 minutes of data acquisition per orbit, downlinked at 3.5 Gbps information data rate through polar ground stations, capacity ~30 Tb/day • 2.88 Gbps direct downlink to India over Indian ground stations, capacity ~10 Tb/day
Observation Approach	• L-band multi-mode global radar imaging • S-band multi-mode targeted radar imaging • Dual-frequency capable • ~240 km swath for all modes • Full pol, multiple bandwidths up to 80 MHz • Near-zero Doppler pointing, fixed boresight • Primarily left or right looking, with occasional flip to the opposite side for better polar coverage
Mapping Approach	Under study – current approach defines a reference mission with fixed modes over broad target areas.

III. DUAL-FREQUENCY RADAR

The NISAR radar characteristics were described previously [5], but are summarized here. To achieve full polarimetric diversity with the noise and ambiguity performance described in Table II over the full swath requires the SweepSAR methodology described below. Work has continued to define the interfaces between the L-band and S-band instruments so that the radars can operate independently or together. The shared oscillator and timing information to lock their pulse repetition frequency together has been designed with simple interfaces. An interface verification test was successfully conducted in December 2016.

The design for the feed apertures has been finalized as mechanically and electrically separate feeds, with manageable coupling. The feeds sit side by side, placing the main beam of each radar off broadside by one beam width. Considerable effort has gone into understanding the electromagnetic environment experienced by the radars and surrounding electronics.

The SweepSAR implementation uses individually addressable Transmit Receive (T/R) modules at both L and S-band. L-band has 12 T/R modules per polarization and S-band has 24. On transmit, all are activated to illuminate the entire feed, which creates a narrow illumination pattern on the reflector in elevation. This in turn creates a broad illumination pattern on the ground. On receive, the echo, which is localized in space and time, reflects off the full area of the reflector, giving maximal signal. As the echo sweeps across the ground and propagates back to space, it is reflected and sweeps across the feed. Each receive channel can track the echo individually, but rather than recording each channel separately and recording all the data, the radars will combine adjacent 3 T/R modules to form a beam that allows a continuous swath to be generated on orbit. This saves data rate to the ground, but requires precise real-time relative calibration of the electronics to ensure the summation of channels is done optimally. Filtering, decimation, calibration estimation, and combining are done in a set of FPGAs or ASICs on each radar. This complication exists for both L-band and S-band, and leads to a multiplicity of parallel processing efforts in the spaceborne electronics. The SweepSAR technique was demonstrated in an airborne configuration to show its efficacy [4].

SweepSAR achieves wide swath because it can track echoes as they sweep across the swath, defeating the ambiguity concerns of typical SAR systems because the receive beam antenna pattern is quite narrow with low sidelobes. However, the radar must pulse fast enough to avoid azimuth ambiguities, so there are actually multiple echoes within the swath that must be tracked simultaneously. The overall architecture of the radar system and the electronics is described in [6].

The observation plan for L-band [5] calls for imaging all land and ice-covered surfaces of Earth on both the ascending and descending parts of the orbit, each orbit. At the northern- and southern-most latitudes where the ground tracks converge sufficiently that there is complete swath overlap, some of the data is discarded. Nonetheless, the L-band radar is operated for up to 50 minutes per orbit, or with a 50% duty cycle. The design of the radar is such that the heat generated by the radar can be efficiently radiated to space to keep the electronics within their operating range. When the radar is not operating, heaters can be applied to warm the electronics. The S-band radar is designed to operate up to 10 minutes per orbit, primarily limited by the ability to remove the heat.

Engineering model hardware exist for all the major L-band technology components, including the T/R module first stage digital process, second-stage combiner, control units, and frequency synthesizers. These subsystems have been tested over temperature, and are currently in revision for the Flight Model units.

TABLE II. SUMMARY OF RADAR CHARACTERISTICS

Element	Description
Operational Implementation	SweepSAR scan-on-receive
Configuration	• 12-m diameter mesh reflector used for both L- and S-band • S-band 2 x 24 / L-band 2 x 12 patch array, one TR module per patch-pair subarray per polarization • Independent S- and L-band electronics with timing synchronization for possible simultaneous operations • Digitization at each receive array element followed by real-time combining
Radar Center Frequency	S-band 3200 MHz; L-band 1260 MHz, simultaneous operations possible
Realizable Bandwidths	• 5 MHz (L) • 10 MHz (S) • 25 MHz (S); 20+5 MHz split spectrum (L) • 37.5 MHz (S); 40 MHz (L) • 75 MHz (S); 80 MHz (L)
Realizable Polarizations	Single-pol through quad-pol, including compact-pol and split-band dual-pol
Incidence Angle Range	~34-48 degrees
Performance	• < -25 dB NES0 depending on mode and swath location • < -15 to -20 dB ambiguities variable across swath • 3-10 m range resolution, sub-pixel geolocation; ~ 7 m azimuth resolution

IV. GLOBAL COVERAGE CHARACTERISTICS

With a 240-km-wide swath and 50% duty cycle, regular sampling of all land and ice surfaces on the globe are planned at L-band. There will also be regular S-band acquisitions over India, Indonesia, and parts of the Arctic and Antarctic of interest to Indian researchers. It is anticipated that as the mission evolves, insights into the most beneficial uses of S-band in place of L-band or as a dual-frequency system will be gained, with the observation plan modified accordingly. These capabilities will provide researchers with a fundamentally new global (at L-band) and globally distributed (at S-band) data set for research. India, where most observations are planned to be joint, simultaneous, L-/S-band multi-polarimetric acquisitions, will be a natural laboratory for frequency and polarimetrically diverse time-series data sets.

Geographic areas of discipline-specific scientific interest often intersect, with each discipline preferring different radar modes. The NISAR science definition team studied a number of observation scenarios and ultimately decided that a regular mapping of Earth with the modes shown in Figure 2 of [5], with full global coverage ascending and descending each 12-day cycle for the life of the mission will lead to robust science for each discipline with minimal mode conflicts. Some thinning of data acquisitions in the northernmost and southernmost latitudes is necessary to keep the data volume to a manageable level. This systematic coverage of Earth for the three-year primary mission will be a major new data set to add to the international constellation of SAR missions. This global observation strategy has been consistent over the formulation period and into development. ISRO has continued to refine the plan focused on India for their applications, which has led to the possibility for considerably more L- and S-band data over India and Indonesia. The capabilities of the ISRO Ka-band telecom system and ground network have grown accordingly to accommodate it.

V. Global Sampling in a Single Spacecraft

In designing a mission concept, there are trades between the capabilities of spacecraft and their cost and complexity. For NISAR, given the prodigious coverage requirements, as well as other programmatic constraints, it was decided early on that the science would be accomplished with a single, highly capable spacecraft. However, given the current trend in developing constellations of small spacecraft, one could imagine attempting to achieve the same coverage goals with a fleet of smaller low cost spacecraft, with lower risk to the mission objectives if a single spacecraft runs into difficulty.

One of the key metrics for a mission like NISAR by which to assess capability is area coverage rate, $\dot{A}$, which is the product of the swath width and the spacecraft ground velocity. NISAR has an area coverage rate of 240 km x 7.2 km/s = 1728 km^2s^{-1}. Small satellites often have smaller apertures, leading to ambiguities that limit their full-resolution swath to on the order of 10-20% of NISAR's SweepSAR swath. For example, one of the more capable small-sat SAR systems is NovaSAR-S [7,8], which has a strip-map SAR swath width of approximately 20 km, which is less than 10% of NISAR. Furthermore, the region over which reasonable performance can be achieved is in a steeper incidence angle range (for NovaSAR-S, 16-31 degrees), which can limit polarimetric performance (surfaces look more similar polarimetrically at steep incidence) and suffer from layover and coarsening of ground resolution.

Another related metric is the on-orbit duty cycle of the system. A number of technical characteristics can limit a system's observational duty cycle: available energy to supply to the instrument over the orbit, available on-board data buffer size, downlink rate and time to offload the acquired data, and thermal limits for operating the active hardware. NISAR is designed for an orbit-average duty cycle of at least 50% at L-band and 10% at S-band. Small satellites typically have smaller power systems – smaller solar arrays and batteries – but similar if not higher demands for power given the smaller apertures. Thus, available energy is typically lower. Planar phased array designs also lead to thermal issues that limit duty cycle. Small satellites typically have 5-10% duty cycles. For example, NovaSAR-S [7,8] has a duty cycle of 3-4 minutes per orbit.

It is instructive to calculate how many small satellites with these characteristics would be needed to achieve NISAR performance. For N satellites in similar orbits to NISAR, each with a duty cycle T_o and full-resolution swath width S, the equivalent number of satellites to achieve NISAR area coverage would be:

$$N_L = \frac{240 \times 0.5}{S \times T_o}\,; N_S = \frac{240 \times 0.1}{S \times T_o}$$

This assumes that each small satellite can only accommodate one radar instrument. For small satellites with 30 km full-resolution swaths and duty cycles on the order of 10%, an equivalent constellation would require 40 L-band radar satellites, and 8 S-band radar satellites. If simultaneous L and S-band observations were needed, many of these satellites would need to fly in tandem, which may necessitate additional satellites to recover area rate.

Repeat pass interferometry adds an additional design constraint that can be a challenge for small satellites. Repeat-pass interferometry dictates that the spacecraft repeat its orbit to within a small range of altitudes and cross-track distances [9]. This control is required for the entire mission, such that imagery acquired at one time in the mission can be combined interferometrically with data acquired at any other time in the mission. Orbit maintenance requires thrusters of some sort and associated fuel load. Higher orbits have lower drag, and therefore are typically easier to control. However, it is often the case that small satellites prefer a lower orbit to minimize power needed to achieve a reasonable radar signal-to-noise ratio. Thus, drag will increase and additional orbit control authority is needed, which may increase the size of the small satellite.

Pointing is another important constraint for the radar for repeat pass interferometry. The system must have sufficient pointing authority to maintain the beam orientation relative to the Earth to within a small fraction of a beam width throughout the orbit over the life of the mission. At L-band, this for a 12 m aperture, the beamwidth is approximately 1 degree, so the control requirement is generally $1/10^{th}$ to $1/20^{th}$ of this beamwidth. For smaller apertures, the requirement is proportionally relaxed, but may still pose a challenge over the entire orbit and over the full mission life. This may lead to a larger control system than those designed for many small satellites.

VI. Current Status

It is with these ideas in mind that the NISAR mission developed as a single satellite to achieve persistent global SAR coverage, with full polarimetric and repeat-pass interferometric capability at L- and S-band.

The NISAR project is currently in development at NASA and ISRO, having conducted a successful Preliminary Design Review in June 2016. The reflector and solid state recorder developments are under contract and in prototyping and engineering model development. All L-band electronics elements are at least at the engineering model stage; some flight models are nearing completion. The planned launch date for the mission is 2021, though the project is looking for opportunities for acceleration.

In the future, scientists are seeking even denser sampling in time, approaching global sampling every day rather than the 6-day sampling (12-days, but observed on both ascending and descending portions of an orbit). The trade of multiple large, complex satellites against an even larger constellation of small satellites may hinge on economies of scale for large constellations that would favor cost efficiencies per unit over the inherent efficiency of a single platform, or possibly on technology advances that reduce the costs of large aperture systems.

ACKNOWLEDGMENT

The authors will like to thank those on the NISAR project and program team, members of the NISAR Science Definition Team, and NASA program managers and scientists for the tremendous efforts in building this complex system on two continents, and their contributions in exploring the trade space that has led to the current mission design.

REFERENCES

[1] Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Ed. by Committee on Earth Science and Applications from Space, National Research Council, National Academies Press, ISBN 978-0-309-10387-9, 2007

[2] Donnellan, A., H Zebker, KJ Ranson. 2008. Radar and Lidar Measurement of Terrestrial Processes. Eos, Transactions American Geophysical Union, Vol. 89, No. 38, AGU

[3] Freeman, A., G. Krieger, P. Rosen, M. Younis, W. Johnson, S. Huber, R. Jordan, A. Moreira, SweepSAR: Beam-forming on receive using a reflector-phased array feed combination for spaceborne SAR. Proc. Radar Conference 2009, Pasadena, CA.

[4] Hensley, S. and 16 co-authors 2011. DESDynI: Achieving multi-displine science objectives through a combination of SweepSAR technology and mission design. IEEE GRSS Symposium, Vancouver, CA.

[5] Rosen, P.A., S. Hensley, S. Shaffer, L. Veilleux, M. Chakraborty, T. Misra, R. Bhan, V. R. Sagi, R. Satish 2015. The NASA-ISRO SAR Mission – An International Space Partnership for Science and Societal Benefit, IEEE Radar Conference 2015, Arlington, VA.

[6] C. L. Chuang et al., "NISAR L-band digital electronics subsystem: A multichannel system with distributed processors for digital beam forming and mode dependent filtering," 2016 IEEE Radar Conference (RadarConf), Philadelphia, PA, 2016, pp. 1-5. doi: 10.1109/RADAR.2016.7485225

[7] R. Bird, P. Whittaker, K. Hall, C. Slim and M. Cohen, "NovaSAR: Next generation developments," *2015 IEEE 5th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*, Singapore, 2015, pp. 94-98. doi: 10.1109/APSAR.2015.7306163

[8] https://www.sstl.co.uk/Downloads/Brochures/115184-SSTL-NovaSAR-Brochure-high-res-no-trims

[9] Rosen, P. A.; Hensley, S.; Joughin, I. R.; Li, F. K.; Madsen, S. N.; Rodriquez, E. & Goldstein, R. M., Synthetic Aperture Radar Interferometry, Proc. IEEE, 2000, 88, 333-382.